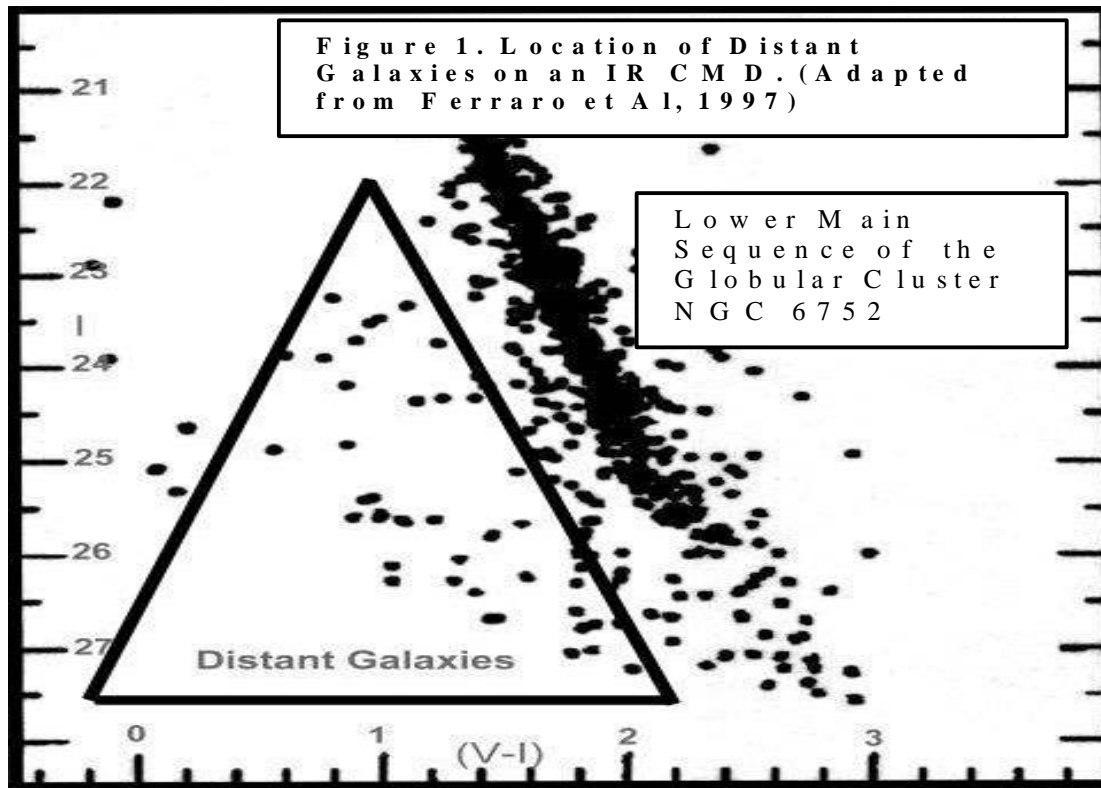# Washington Photometry of the Old Galactic Globular Cluster M92.

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S. D. Gillam   J.P.L. Table Mountain Observatory
Dee Asbury   Los Angeles City College
Charles Jordan III Los Angeles Southwest College
Jasmine Patton   Los Angeles Southwest College
Janelle Rodriguez   Los Angeles City College

Distances and Ages

Globular clusters (GCs) formed, with galaxies, ~ 1 Gyr after the big-bang (Chaboyer, 1995). GCs are 15-18 Gyr old (VandenBerg, 1983). Precise ages from luminosity functions (LFs) will be used to precisely estimate of the age of the universe. Accurate [Fe/H] values and oxygen abundances are also required (Geisler, et Al. 1992). Distances, ages and [Fe/H] will be separately measured and combined to check consistency.

Figure 1. Location of Distant Galaxies on an IR CMD. (Adapted from Ferraro et Al, 1997)

Lower Main Sequence of the Globular Cluster NGC 6752

Distant Galaxies
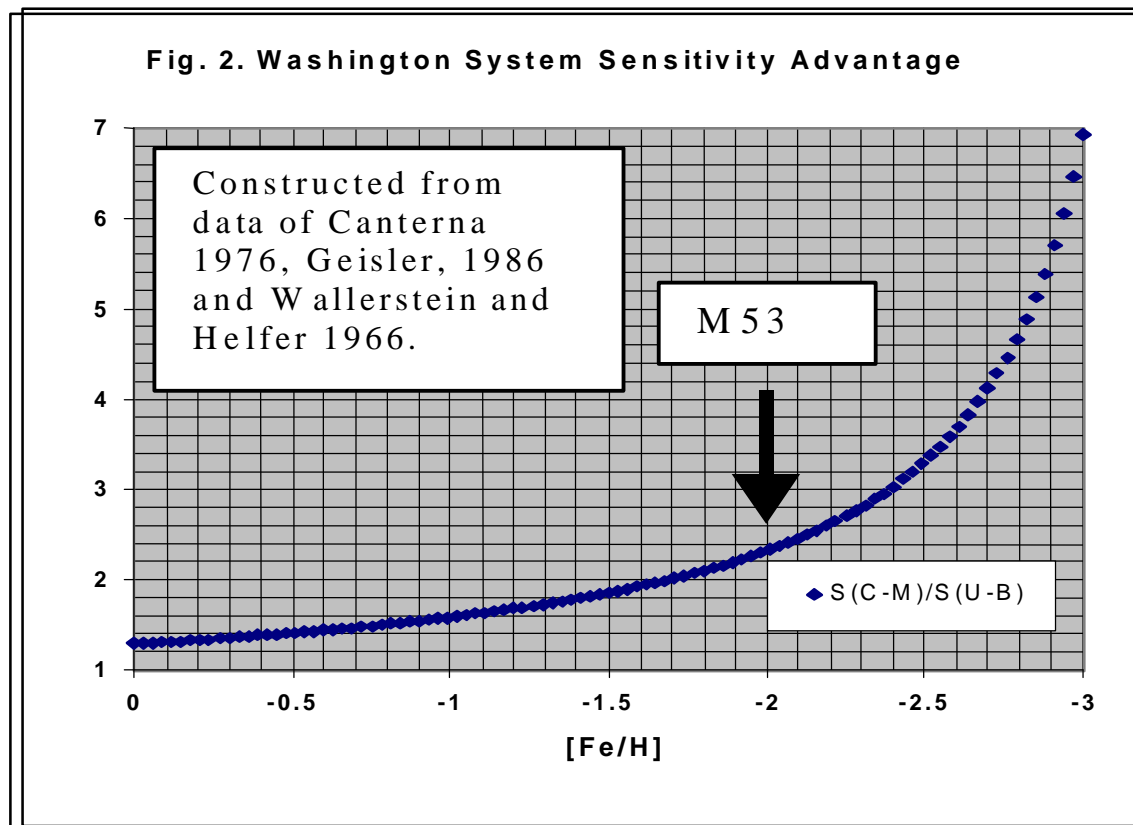
Distances to Globular Clusters

Distances to GCs will be found, *independently of reddening and metallicity,* from the parallactic motions of their centroids. as measured from positions of the stars ($>10^4$) in their cores on High-resolution HST images taken ~1Year apart. There are ~20-40 Galaxies (I =22-25) in these images (Griffiths et Al, 1993). They will be used as non-moving reference objects. They occupy the triangular region in Fig. 1 Few are stars because the target GCs are well out of the galactic plane (See table 1). CMDs will constructed from archival WFPC2 data already procured from STSCI.

Ages

Absolute ages will be derived from luminosity functions *independently of distance.* Ratios of star counts in adjacent sub-giant luminosity bins measure age to +/-0.5GYr. (Bergbusch and
VandenBerg, 1997, Padoan and Jimenez,1997,Piotto et. al., 1999).

Metalicities

Metalicities of GC stars will be estimated from (C-M) and (M-Mould I) colors using the calibrations of Geisler et Al. 1991. This method is as good as low-precision spectroscopy and much more efficient. *This data will be obtained from TMO because HST lacks Washington filters.* Precise [Fe/H] measures for old GCs require E(B-V) errors < +/-.03. (Geisler, 1991). Reddenings to all GC giants will be estimated by comparison of observed to intrinsic (J-K) colors; where line-blanketting is absent and the stellar flux can be accurately modeled (Arribas et Al, 1987). HST NICMOS data has been procured for this task. The *[Fe/H] sensitivity* of the Washington (C-M) color is significantly greater than (U-B) for old, metal-poor, GCs. See figure 2 (Compiled from many sources.)

Fig. 2. Washington System Sensitivity Advantage

Constructed from data of Canterna 1976, Geisler, 1986 and Wallerstein and Helfer 1966.

M 53

S(C-M)/S(U-B)

[Fe/H]

The quantity S(C-M)/S(U-B) plotted in figure 2 is the ratio of the sensitivity of the Δ(C-M) index (Geisler, 1992) to that of the δ(U-B) index (Wallerstein and Helfer, 1966). S(C-M) = Δ(C-M) / [Fe/H] and S(U-B) = δ(U-B) / [Fe/H]. The arrow marker "M53" indicates the approximate [F/H] of the least metal poor of the old program clusters. At this point the Washington-DDO sensitivity advantage has become significant.

Contamination of Giant Branches by Field Stars

Contamination of GC giant branches by field dwarves, with the same effective temperatures and apparent magnitudes, will be removed on the basis of atmospheric Mg absorption strengths, using the "51" filter (McClure, 1979). (M-51) colors will be plotted as they are almost unaffected by reddening because the center wavelength of the 51 and M filters are almost the same. This allows giants to be separated from dwarves without a detailed knowledge of the reddening to each star in the field. *(M-51) will be obtained at TMO because HST lacks an Mg filter*. In addtion (M-51) is a more sensitive temperature index than (C-M). Comparison of Figures 3a. and 3b. shows that the (C-M) index is as marginally tighter than the (M-Mould I) but the latter is more useful for the most distant clusters. This is because the C filter becomes insensitive to the fainter giants in the

distant and redder clusters The ability of the Mg index is illustrated, using field stars, in fig. 3. Each figure is based upon the same set of field stars. These were dereddened to approximate the essential fact that the stars in clusters all at the same distance.
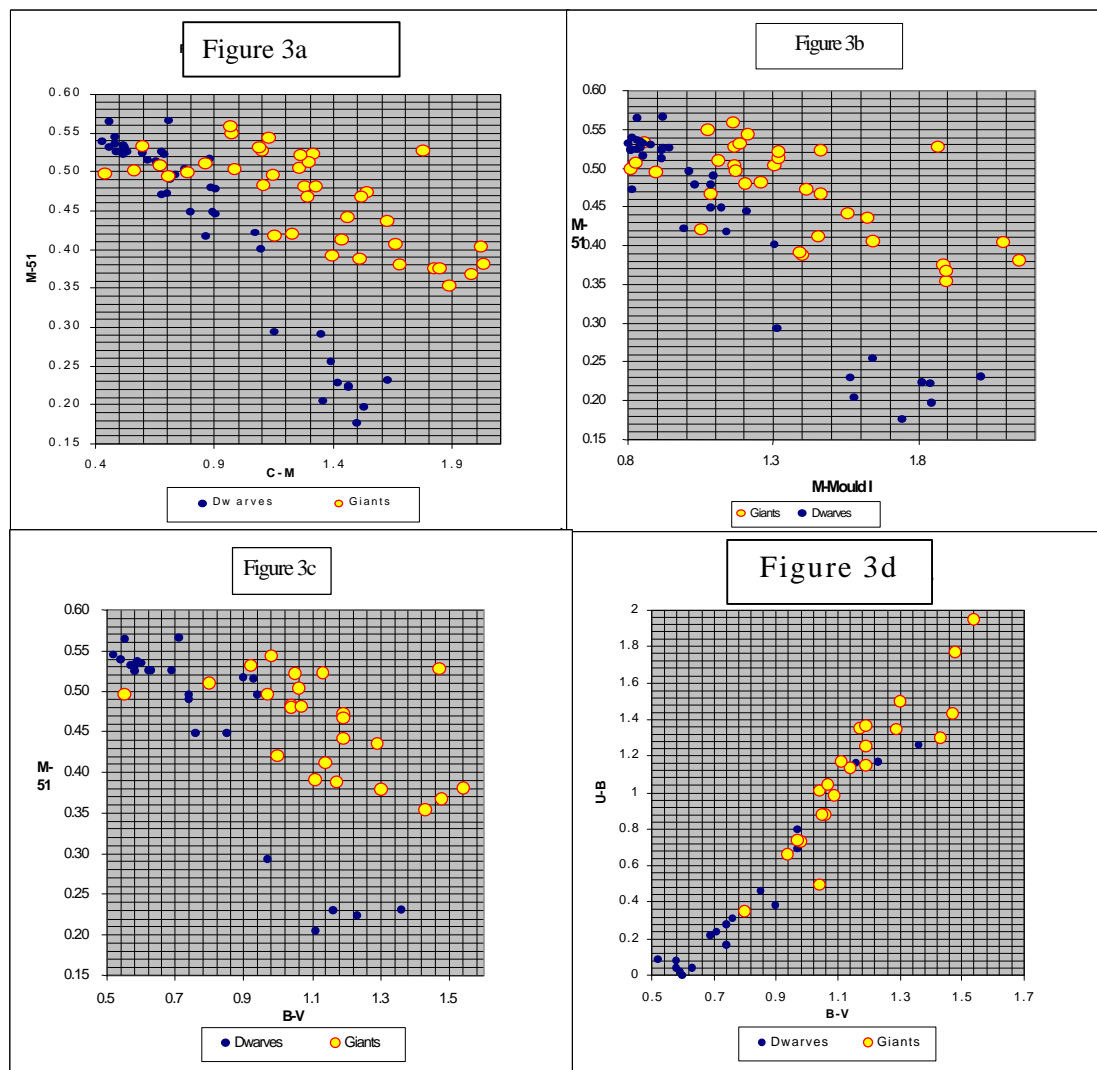

Figure 3a

Figure 3b

Figure 3c

Figure 3d

Figure 3. The performance Washington-DDO and UBV giant/dwarf discriminators. 3a. Mg Index vs (C-M). 3b. Mg Index vs (M-Mould I). 3c. Mg Index vs (B-V). 3d Traditional (u-B) vs (B-V). The (M-51) color is the Mg Index.

Comparison of the ordinates of figures 3a – 3c shows that (C-M) ans (M-T1) are considerably more sensitive to temperature than (B-V). This feature will also be exploited to separate cluster giants from field dwarves. Figure 3d shows that (U-B) vs. (B-V) does not separate giants from dwarves at all.

The TMO Washington Filter Set

The filter set used at TMO was purchased from the Omega Optical Company in a group-buy with C.T.I.O. These filters closely approximate the original design (1). The curves are reproduced from data supplied by Omega Optical. The horizontal scale is nanometers. The vertical scale is relative sensitivity.

Response Functions of Filters Used at JPL Table Mountain Observatory
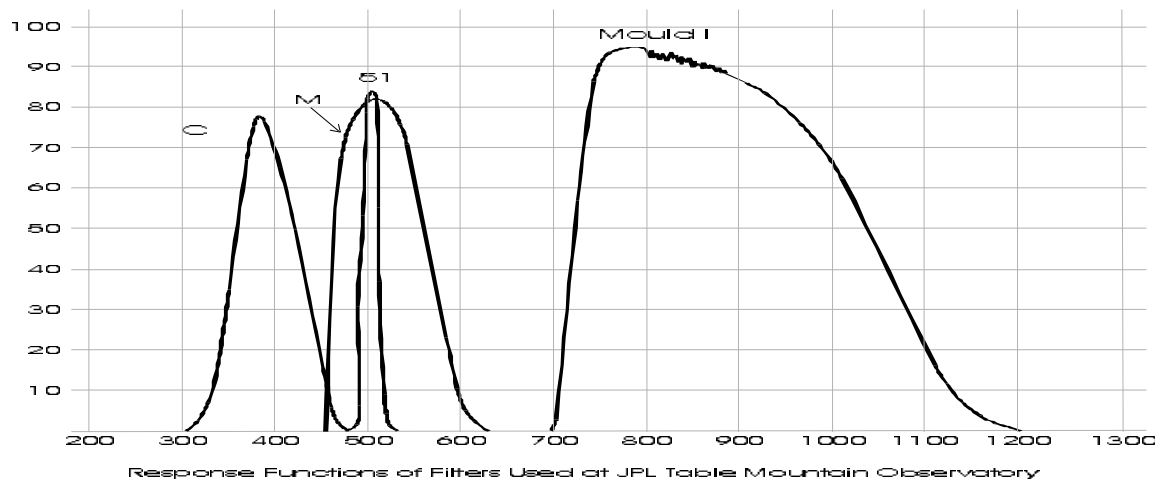
The Canterna filter set is shown for comparison. It was adapted from (1). The Mould I filter (above) is used in place of the T2 filter (below). It is simpler and cheaper than the T2 filter. The TMO set includes a T1 filter but it is not used.
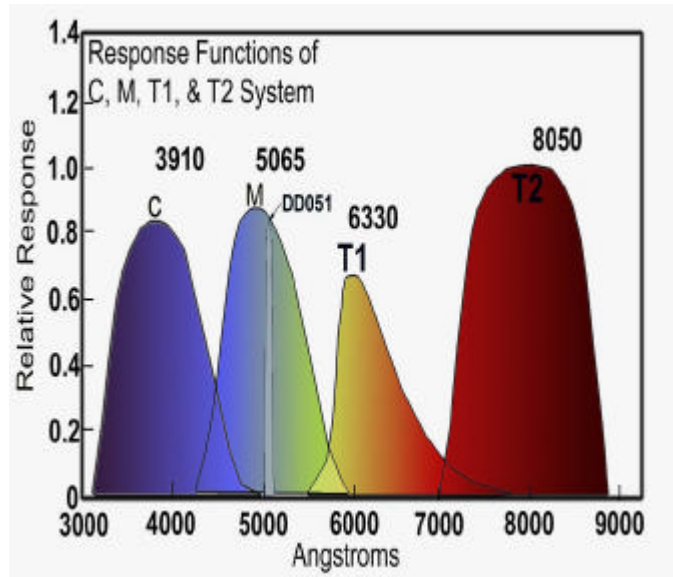
The Mould I filter has considerable excess response longward of 900 nm when compared to the T2 filter. The effect this "red-leak" has on the ability of the Mould I to reproduce T2 magnitudes will be investigated.

Observations

One-hour C, M, Mould I and 51 exposures down to 20th mag (S/N ratio>100) will be made to precisely measure the sub-giants and turn-off stars for the LF age estimate and provide the precision (+/-.003 dex) needed to separate giants and dwarves with (C-M) < 1.0.

The telescope tracking will be constantly corrected for atmospheric refraction. Exposures will be taken when clusters are on the meridian to minimize atmospheric refraction and extinction. The 1024x1024x24μm LN2-cooled CCD camera on the TMO 0.6-m telescope provides an FOV of 8.7 x 8.7 arcmin. All the clusters in table 1 can be adequately covered with a grid of 4 overlapping

fields in each filter. GC observations already made prove that round star images can be obtained in 1-hr exposures (1999 AAS 195 03.16). Stacks of short exposures are not needed and the data volume is greatly reduced.

Table 1. Target Globular Clusters

Name	RA	Dec	b	E(B-V)	VHb	RGc	Fe/H	Rt.	Amax
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
4147	12:08	19	+77.19	0.02	16.85	19.9	-1.80	7.244	1.037
M53*	13:10	18	+79.77	0.00	16.94	19.2	-2.04	21.878	1.042
5053*	13:14	18	+78.94	0.01	16.63	16.7	-2.17	13.804	1.042
M3	13:40	29	+78.71	0.00	15.68	12.6	-1.66	38.905	1.004
5466*	14:03	29	+73.59	0.00	16.6	16.4	-2.22	20.893	1.004
M5	15:16	02	+46.8	0.03	15.11	6.6	-1.40	28.84	1.184
M13*	16:40	37	+40.91	0.03	14.95	8.9	-1.65	26.915	1.001
M92*	17:16	43	+34.86	0.02	15.1	9.8	-2.24	16.596	1.011
M72	20:51	-13	-32.68	0.03	16.85	12.7	-1.54	8.71	1.477
M2	21:31	-1	-35.78	0.02	16.05	10.9	-1.58	16.218	1.227

(1) cluster name, (2) RA in hrs. and mins. , (3) Dec in degress, (4) Galactic latitude in degrees, (5) interstellar reddening, (6) horizontal branch apparent magnitude, (7) galactocentric distance in Pc, (8) Fe/H, (9) tidal radius in arc min. and (10) minimum airmass at TMO. An asterisk indicates those considered to be the oldest (Chaboyer, 1995)
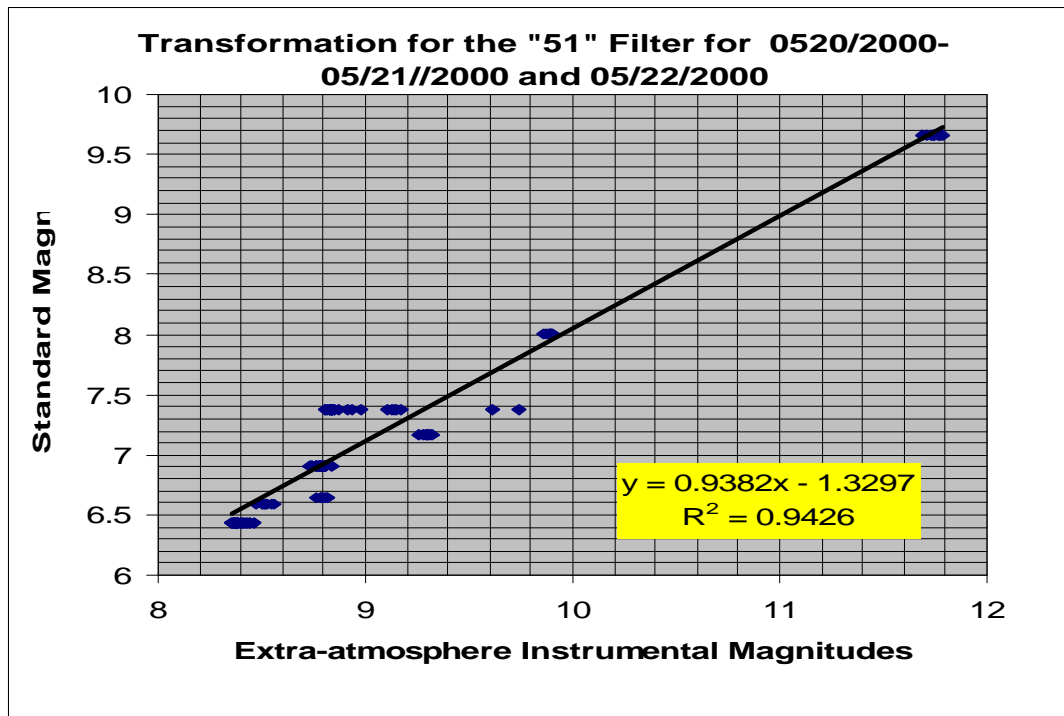
Dark-time is required. Two cluster frames and an array of standard star fields will be collected each night. 3 nights per month will be requested. Eight nights per cluster is required. Approximately half the data has already been collected. Another 3 years is required to complete the data collection. A team of 4 CURE students is responsible for collecting the astronomical data and 2 more are involved in data reduction at any time. Up to 20 students will be involved over the lifetime of the project. Targets are scheduled by the mentor using s/w developed for the project.

Calibrating the TMO DDO51 Filter

The TMO "51" is filter similar to the David Dunlap Observatory (DDO) 51 filter (1). It was calibrated with published DDO Standards (1) & (2). Stars with $M_{51} > 6.00$ were chosen so that

a) The exposures would not saturate,
b) 20 and 30 sec that the shutter dwell time was less than 1% of the exposure time, and
c) The list contained approx. one per hour, and
d) A large range of magnitudes was included.

Ten observations of each star were made per CCD frame by shifting star images between exposures and then reading out the frame. This minimized the readout overhead (26seconds per full frame) and provided a means of observing the same stars many times to reduce the errors.

Transformation for the "51" Filter for 0520/2000–05/21//2000 and 05/22/2000

$y = 0.9382x - 1.3297$
$R^2 = 0.9426$

114 observations of 8 stars were accumulated on 5/20, 5/21 and 5/22/200. These are plotted above. The weather was excellent both nights and a single transformation was derived.
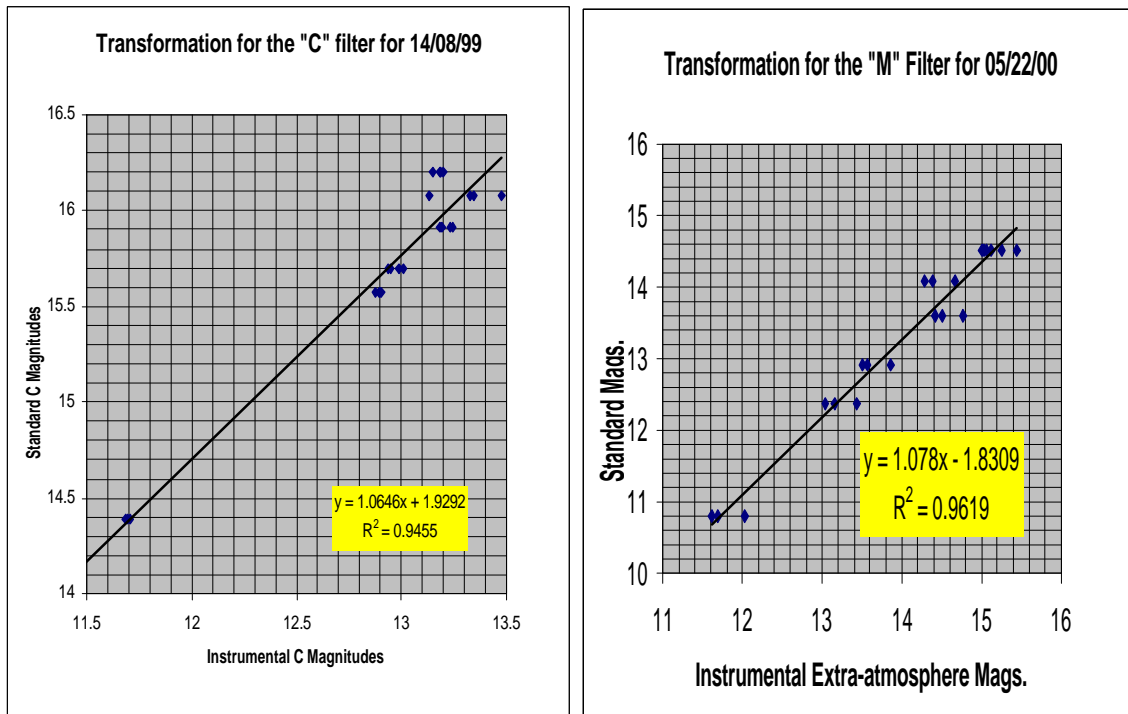
$$M = .9382m + 1.3297$$

Where M is the standard 51 magnitude and m is the extra-atmosphere instrumental magnitude. The scatter in the measurements of the faintest star is 0.09 mag.
 No data was available to estimate the airmass correction for this filter, so the airmass coefficient estimated for the "M" filter was used.

The C, M and 51 Filter Standard Transformations

Preliminary transformations from instrumental C, M and 51 magnitudes to the standard system have been generated for several nights. The plot below shows one example. This transformation is required to standardize the available C filter cluster data.

Transformation for the "C" filter for 14/08/99

$y = 1.0646x + 1.9292$
$R^2 = 0.9455$

Standard C Magnitudes (y-axis)
Instrumental C Magnitudes (x-axis)

Transformation for the "M" Filter for 05/22/00

$y = 1.078x - 1.8309$
$R^2 = 0.9619$

Standard Mags. (y-axis)
Instrumental Extra-atmosphere Mags. (x-axis)

This C transformation was constructed from 24 observations of 6. The M transformation were constructed from a similar set of observations. Both used the SA107 field (Geisler, 1995).

Date UT	Filter	Slope	Zero point	R-Value
04/14/98	C	.9941	2.5774	.9764
04/14/98	C	1.0087	2.5053	.995
07/17/98	C	1.0681	1.922	.9913
04/18/99	C	1.0638	1.3949	.9972
04/19/99	C	1.0893	1.3401	.9894
08/14/99	C	1.0646	1.9292	.94.55
09/12/99	C	1.1629	1.3788	.9197
05/22/00	C	.1.133	.3572	.9703
05/22/00	M	1.078	-1.8309	.9619
05/22/00	51	.9382	-1.3297	.94

The above table indicates a consistency of slopes to a few percent over 2 years. This shows that the camera operation is very stable and that it is reasonable to combine data from all 40 nights to get high-precision cluster photometry. The precision of these transformations will be improved when more data is included in them.
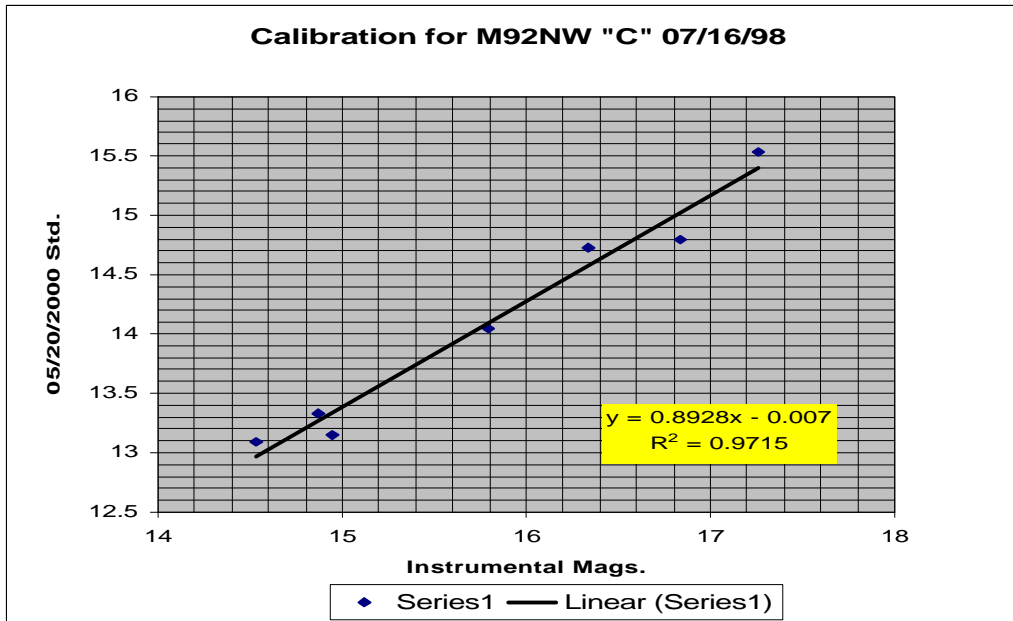
Transferring the Photometric Calibration

Many nights lack sufficient standard stars to perform photometric calibration or the sky transparency was variable. In these cases the photometry was calibrated against data from good nights. The limiting magnitude of these frames was smaller and the photometry limited to brighter stars. Two examples are shown below for one-hour exposures.

08/20/98: The slope is approximately unity – similar to calibrations for other nights. The zero point includes the difference in sky transparency between the two nights.


Calibration for M92NW 51 08/20/98

$y = 1.1192x - 5.2517$
$R^2 = 0.8588$
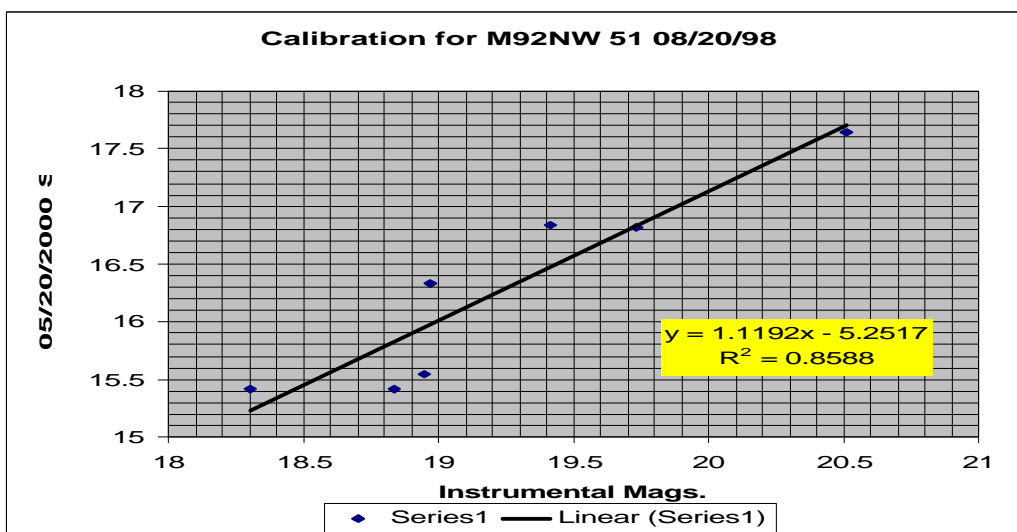
07/16/98: This is a high-precision fit. The zero point difference is very small. The slope is not unity.

Calibration for M92NW "C" 07/16/98

$y = 0.8928x - 0.007$
$R^2 = 0.9715$

05/20/2000 Std. (vertical axis)

Instrumental Mags. (horizontal axis)

◆ Series1 ── Linear (Series1)

Photometric Precision of Cluster Measurements

The graph below illustrates an attempt to estimate the precision of the M filter photometry. The magnitude difference between 278 stars common to two 10-minute frames, taken on 05/20/2000 and 05/22/200 is plotted against the mean of those magnitudes.

The graph overall has the typical fan-like appearance due to photometric errors increasing with magnitude. There is a mean difference of about 0.1 magnitudes between the two frames and scatter in magnitudes of approximately 0.2 mags. This extends for four magnitudes (to m=30). At fainter magnitudes the dispersion increases to approx. 1.5 magnitudes.

**Dispersion in Instrumemental "M" Magnitudes Between 05/20/200 and 05/22/2000**
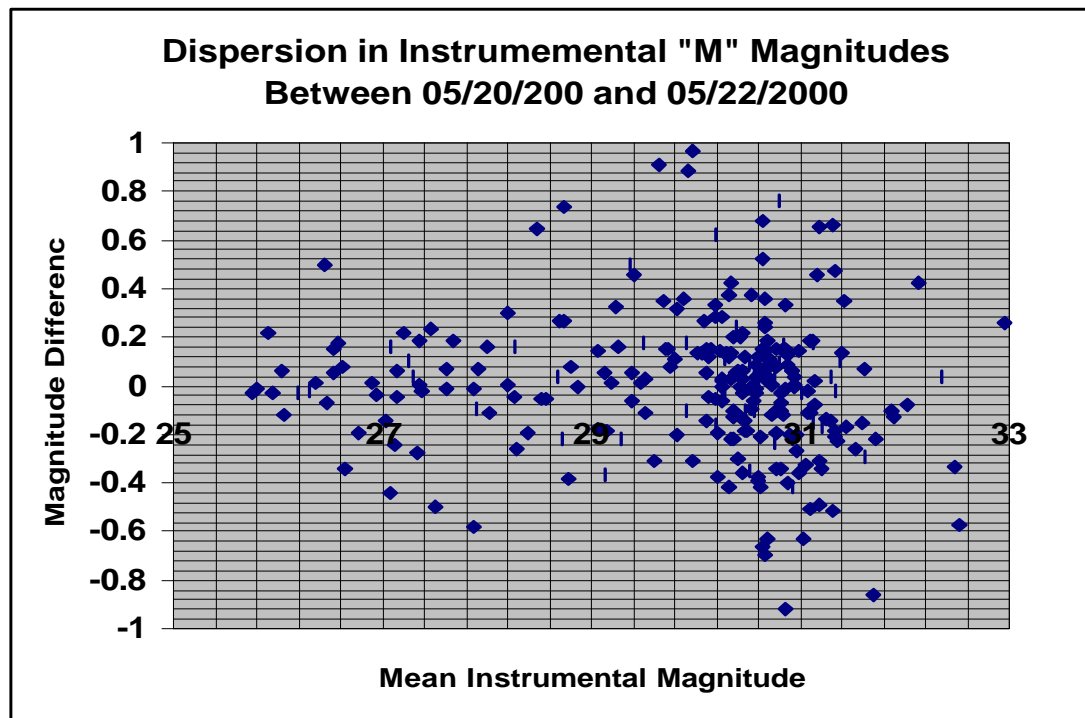
Clearly, more data is required to more closely determine precision. More data is available for this purpose

The 51, (C-51) Color-Magnitude Diagram of M92

The 51, (C-51) color-magnitude diagram for M92 is presented below. It consists one-hour C and 51 frames from 7/16/98 and 8/20/98 resp. DAOphot was used to extract the instrumental magnitudes. These were:

a) Cross-calibrated with a subset of the photometry from 05/22/2000,
b) Corrected for airmass using relations derived from other good nights in 1998 and 1999,
c) Transformed to the standard system using the relations presented in this paper, and
d) Combined on the basis of positional coincidence.
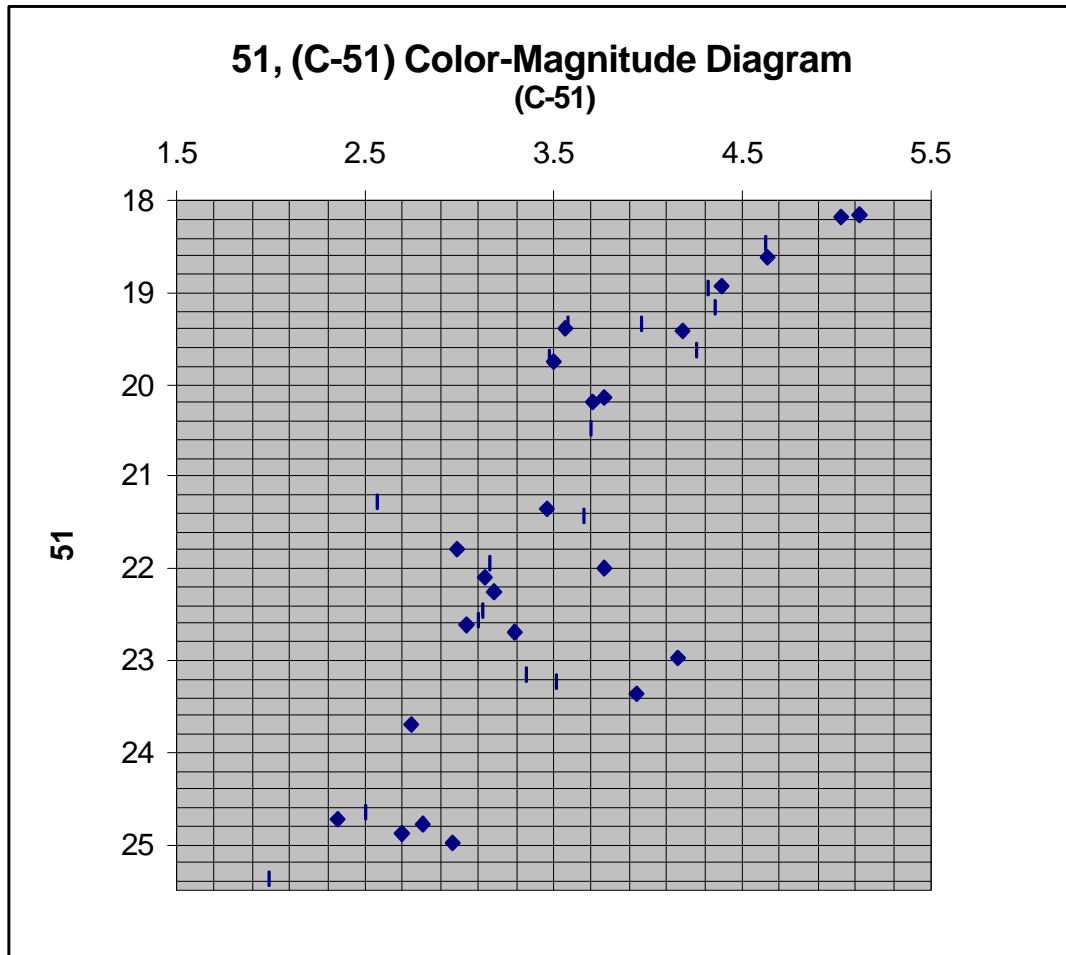
This CMD includes 40 stars selected from the C and 51 photometry lists on the basis of stringent coincidence criteria. Colors were formed only from stars in the C and 51 frames having X and Y coordinates differing by less than 0.4 pixels. In addition only objects with individual random errors of less than 0.01 magnitudes and those with the best PSF fitting statistics were used.
A well-defined upper giant branch is visible.

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[#] Used, in conjunction with [!] to construct Figure 3a – 3d.